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RESEARCH MEMORANDUM

INVESTIGATION OF TRANSIENT COMBUSTION CHARACTERISTICS IN A SINGLE TUBULAR COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the combustion response to rapid fuel-flow changes in a single tubular combustor at two simulated altitude - rotor speed conditions of 25,000 feet - 70 percent rated engine speed and 50,000 feet - 70 percent rated engine speed. Limiting rates of change of fuel flow (acceleration limits) were determined and the effects of certain combustion air flow variables on the transient combustion characteristics were studied with the aid of rapid-response instrumentation.

The combustion followed one of three paths in response to rapidly increased fuel flow: (1) successful operation at higher levels of temperature, pressure, and fuel-air ratio; (2) temporary operation at higher levels of output climaxed by blow-out; or (3) immediate blow-out (quench-out). The data indicated that as the rate of change of fuel flow was increased, blow-out occurred at lower final fuel-air ratios. With very rapid fuel-flow changes, combustion quench-out occurred. Acceleration limits were determined as functions of rate of change of fuel flow and final fuel-air ratio at the several operating conditions investigated. As altitude was increased, the combustion stability and the steady-state fuel-air ratio limit were reduced, resulting in a reduction in acceleration limits. A study of the individual effects of combustion air-flow variables indicated that: (1) As combustor-outlet gas temperature, before the fuel flow was changed, was increased, the acceleration limits were increased; and (2) for a given initial heat-release rate, combustor-inlet-air static pressure affected the maximum rate of change of fuel flow only by affecting the steady-state blow-out limits. The increase in acceleration limits with initial outlet temperature suggests that the initial heat-release rate may be an important parameter controlling acceleration.

INTRODUCTION

Among the problems associated with turbojet engine operation at high altitude is the inability of the engine to accelerate rapidly in response to increased fuel flows. Research is being conducted at the NACA Lewis laboratory to determine the factors affecting engine acceleration and to study methods of improving acceleration characteristics.

Engine acceleration has been found to be detrimentally influenced by compressor instability and by the inability of the combustor to produce adequate temperature rise. For example, a study of one full-scale engine indicated that compressor instability limited acceleration at altitudes less than 35,000 feet, whereas combustion flame-out was the limiting factor at altitudes greater than 35,000 feet (ref. 1). In order to avoid unstable compressor and combustor operating conditions it is necessary to maintain precise control of the fuel input to the combustor during acceleration. The influence of a change in fuel flow, in addition to other combustor variables, during engine acceleration has been further demonstrated by studies conducted in small-scale laboratory burners (ref. 2). 3062

The investigation reported herein was conducted to study the temperature-response characteristics of a single full-scale tubular combustor to rapidly varying fuel flows, with a view to obtaining a better understanding of acceleration problems encountered in the full-scale engine. An attempt was made to approximate conditions existing in the full-scale engine combustor before and after an advance in the fuel throttle setting. Choke plates were placed in the inlet and exhaust ducting of the combustor to provide critical flow at positions corresponding to the last compressor stage and the turbine inlet. At selected simulated engine operating conditions, fuel flow was increased at predetermined rates. These rates of change of fuel flow are herein denoted by the term acceleration rate. The transient combustor variables - inlet air pressure, combustor-outlet temperature, and fuel flow - were measured by rapid-response sensing elements connected to high-speed recorders.

Data were obtained at combustor conditions corresponding to 50,000 feet altitude - 70 percent rated rotor speed and to 25,000 feet altitude - 70 percent rated rotor speed in a reference turbojet engine. A number of tests were conducted at other operating conditions in order to determine the effects of initial (before acceleration) outlet temperature, inlet-air pressure, and air-flow velocity on the response characteristics. The data are analyzed to indicate the response characteristics of the combustor and to determine the fuel acceleration limits at the selected operating conditions. Visual and photographic observations of the fuel spray and of combustion during acceleration are also discussed. Detailed descriptions of the special apparatus and instrumentation used are presented.

APPARATUS AND INSTRUMENTATION

Combustor Installation

A schematic diagram of the single tubular combustor installation with planes of instrumentation indicated is shown in figure 1. The combustor was a production-model J35 unit; inlet and exhaust duct sections were fabricated to simulate corresponding engine parts. Combustor air flow was measured by means of a variable-area orifice. Air flow quantity and pressure were regulated by remote-control butterfly valves located upstream and downstream of the combustor. Location and construction of the inlet and outlet choke plates are shown in figure 2. The inlet choke plate, which admitted air through fifty 1/4-inch-diameter holes, was installed in the inlet ducting at a position corresponding approximately to the last stage of the compressor in the full-scale engine. The outlet choke-plate assembly consisted of two slotted plates, one of which was movable with respect to the other, permitting a wide range of flow areas to be selected. The outlet choke-plate assembly was located at a position corresponding to the turbine nozzle diaphragm in the full-scale engine. A standard dual-entry duplex fuel nozzle was used throughout the investigation. Separate lines supplied fuel to the large and small nozzle slots. The fuel used was MIL-F-5624A, grade JP-4 (NACA 52-288).

Fuel Acceleration System

The system used for fuel acceleration control is shown in figure 3. Fuel accelerations were obtained by means of a valve designed to provide a fuel-flow increase that was nearly linear with valve shaft travel. An electric motor was coupled through a variable-speed transmission to a flywheel on the drive shaft. The flywheel shaft was connected to the valve shaft through a solenoid-actuated clutch-brake assembly. The amount of opening or closing of the valve was controlled by two variable-position microswitches which limited the amount of travel of a thin metal disk mounted on the valve shaft. When the traveling disk made contact with either of the microswitches, the clutch was immediately disengaged and the brake was energized, thus limiting valve travel to a preset amount. Fuel for acceleration was supplied to the valve from a nitrogen-pressurized reservoir at pressures ranging from 0 to 300 pounds per square inch gage. The accelerating fuel system was connected to the standard fuel system as shown in figure 3 and contained standpipes of various capacities which could be opened or closed to alter the surge characteristics and acceleration rate of the fuel inputs.

Instrumentation

Detailed sketches of instrumentation and the respective locations in the test duct are presented in figure 2. Combustor-inlet-air temperature was measured by two single-junction iron-constantan thermocouples located at station 1 (fig. 1). Steady-state combustor-inlet static pressure was measured by means of static taps located at station 2 (fig. 1). Transient combustor-inlet static pressure was measured at the same station (2) with a diaphragm-type differential pressure pickup. The transient fuel flow was measured with a similar unit connected across an orifice in the large-nozzle-slot supply lines (fig. 3). The orifice in the large-slot line simulated the effect of a flow divider, providing some improvement in spray formation at low fuel flows. Dynamic response characteristics and design features of the diaphragm pressure-pickup installations are given in reference 3. The inlet static pressure and fuel pressure differential were recorded on an oscillograph.

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Combustor-outlet temperature was measured by three five-junction chromel-alumel thermocouple rakes located at station 3 (fig. 1). These rakes were designed to provide rapid response to exhaust-gas temperature changes. The individual junctions on each rake consisted of 0.010-inch-diameter wires butt-welded between two heavier support wires (fig. 2). The combustor-outlet thermocouples were connected through an averaging circuit to an oscillograph. During this investigation the indicated average combustor-outlet temperature, before and after a fuel acceleration, was obtained from the oscillograph record. The rapid variations in combustor-outlet temperature during the acceleration process were indicated by a single thermocouple circuit compensated for thermal lag and were recorded by another oscillograph. The thermocouple that most nearly indicated the average reading of the 15 combustor-outlet thermocouples at station 3 was selected for the transient measurements. Because of differences in temperature profile, it was necessary to use different thermocouples at the different operating conditions investigated. A comparison of compensated and uncompensated thermocouple responses to temperature changes of equal rate and magnitude is presented in figure 4. The uncompensated thermocouple circuit had a time constant of approximately 0.3 second, whereas the compensated thermocouple circuit had a reduced time constant of approximately 0.015 second. The compensating circuit was adjusted by setting test air-flow conditions in the combustion chamber and feeding a heating current across the thermocouple. The variable-resistance inductance in the compensator was then adjusted until a step function was produced on the oscillograph when the heating current was discontinued. The theory of compensation is presented in reference 4.

PROCEDURE

Test Condition

Transient combustion-response characteristics were studied at the following operating conditions (flight Mach number, 0):

Simulated flight conditions		Inlet static pressures, in. Hg abs	Inlet-air tempera-ture, °F	Reference velocity, ft/sec	Initial combustor-outlet temperature, °F
Altitude, ft	Rated rotor speed, percent				
25,000	70	28.0	80	82	675-700
50,000	70	9.3	80	82	675-700

With the exception of inlet-air temperature, these conditions simulated operation of the combustor in a 4.7-compression-ratio turbojet engine at the flight conditions noted. The reference velocity values quoted are based on the maximum cross-sectional area of the combustor (0.48 sq ft) and the inlet-air density.

Additional data were obtained to describe the independent effects of combustor air velocity and initial outlet temperature on the combustion response characteristics. The conditions investigated are as follows:

Inlet static pressure, in. Hg abs	Air flow, lb/sec	Inlet-air tempera-ture, °F	Initial combustor-outlet tempera-ture, °F	Combustor reference velocity, ft/sec
28.0	2.70	80	290	82
28.0	3.26	80	265	100
28.0	2.02	80	375	60
9.3	.90	80	500, 800, 1000	82
9.3	.68	80	940	60

Test Procedure

Prior to each set of test runs, the oscillograph recorders were calibrated against standard measuring instruments. The averaging thermocouple circuit and the single compensated thermocouple circuit were calibrated against a self-balancing potentiometer; the transient static-pressure recorder was calibrated against a manometer connected to the test duct in the same plane; and the fuel flow recorder was calibrated against a rotameter in the fuel system. At selected combustor-inlet test conditions, combustion was initiated and fuel flow was set at the desired initial value by means of the remote-control throttle valve (fig. 3).

At each of the selected operating conditions, the fuel flow was increased from its initial value to a higher value required for acceleration. The fuel-against-time trace indicated that the fuel-flow increase was a ramp function. For selected values of final fuel flow, the slope

of the fuel ramp was increased until combustion blow-out occurred; the limiting slope or acceleration rate represented the acceleration limit. In general, the maximum final fuel flow investigated was the steady-state rich blow-out limit, determined prior to the actual acceleration tests. At several conditions investigated, the maximum final fuel flow was limited by the capacity of the fuel system. The fuel for acceleration was injected into the fuel nozzle supply line by the accelerating fuel system (fig. 3) in the following manner. The pressure in the nitrogen-loaded fuel reservoir was set equal to or less than the pressure upstream of the remote-control throttle valve (fig. 3) to minimize flow back into the fuel supply system during acceleration. The motorized valve transmission speed 3062
and limits of travel were selected and the various standpipes were opened or closed as desired. Fuel accelerations were obtained by starting the electric valve motor and allowing it to reach full speed and then energizing the drive-shaft clutch. This procedure was repeated with varying settings of the components of the accelerating fuel system in order to obtain a range of fuel acceleration rates.

Method of Analysis

The fuel acceleration rates referred to herein represent the slopes of the fuel ramps and were computed as the change of fuel-air ratio per unit of time. Figure 5 represents a sketch of a typical fuel ramp trace. The acceleration rate was calculated by subtracting the initial fuel-air ratio and dividing the difference by the amount of time (sec) between the point on the trace where the acceleration begins and the point where the fuel flow first reaches the desired final fuel flow. A fuel "overshoot" was indicated during rapid fuel accelerations, as shown in figure 5. This overshoot could be minimized by a proper selection of the fuel accumulators (standpipes) shown in figure 3, but could not be eliminated entirely.

RESULTS AND DISCUSSION

Results obtained in the investigation of the effect of fuel acceleration on combustion response characteristics are presented in tables I to IV. A total of 175 acceleration tests were conducted; tables I to IV present condensations of the data obtained including operating conditions, fuel acceleration rates, and resultant effects on combustion.

Combustor Response Characteristics

Oscillograph records typical of those obtained at the simulated 50,000-foot altitude - 70 percent rated rotor speed condition are presented in figure 6. The oscillograph records show the variation of fuel flow, inlet static pressure, average outlet gas temperature, and compensated outlet temperature indication (from the single compensated thermocouple). The test data presented in figure 6 illustrate the three alternate paths which the combustion process may follow during fuel acceleration:

(1) The additional fuel may ignite and burn stably, resulting in increased temperature rise (fig. 6(a)).

(2) The additional fuel may ignite, temporarily burn at a higher outlet temperature level, and then blow out (fig. 6(b)).

(3) The combustion may blow out immediately after the fuel acceleration is begun (fig. 6(c)).

For purposes of discussion, the second and third types of combustion failure will hereafter be differentiated by referring to them as blow-out and quench-out, respectively. In order to illustrate more clearly the effect of fuel acceleration on the combustion process, a composite plot of the data from figure 6 is presented in figure 7, showing faired curves for the fuel flow, compensated outlet temperature, and static-pressure variations at the 50,000-foot altitude - 70 percent rated speed conditions. The steady-state blow-out limit is included in figure 7 to compare the relative values of the final fuel flow rates obtained in the three tests. The blow-out limit was not precisely reproducible, ranging from fuel flows of 100 to 110 pounds per hour. It is noted (fig. 7) that the outlet temperature and the static pressure decreased with the initial introduction of additional fuel and then increased when the fuel ignited and burned. For fuel-flow changes slower than those shown in figure 7, the temperature and pressure followed the increase in fuel flow with little or no initial decrease.

Figure 8 presents typical data obtained at the simulated 25,000-foot altitude - 70 percent rated rotor speed conditions. Steady-state blow-out at these conditions was not encountered for the temperature range studied in figure 8. Results of four acceleration tests of varying acceleration rates are shown; it is noted that successful accelerations were obtained in all cases. A comparison of these data with the data of figure 7 indicates that much more rapid accelerations were possible at the lower altitude condition (fig. 8). The temperature and pressure increases following fuel acceleration were also more rapid at the lower altitude, indicating increased responsiveness to acceleration as altitude is decreased. The time between the start of the fuel acceleration and the point where the temperature and pressure first exceeded their initial values was less than 0.25 second at the low-altitude conditions (fig. 8), compared to a time of 1.75 to 2.0 seconds for the high-altitude condition as indicated by test results.

The results presented in figures 7 and 8 show that fuel overshoot occurred during acceleration; however, the indicated overshoot was not a quantitative measure of the actual fuel overshoot occurring at the nozzle since the measuring instrumentation was affected by recirculation within the duplex nozzle. The actual overshoot probably followed a qualitative pattern similar to that indicated in figures 7 and 8, however. The initial decrease in outlet temperature and static pressure may have been influenced by the overshoot present, as well as by the fuel acceleration rate; the amount of decrease increased with increased overshoot and acceleration rate. Attempts to eliminate overshoot during rapid acceleration in order to determine the extent of its influence were not successful. 3062

Additional tests were conducted at the two simulated altitude conditions with the inlet and outlet choke plates removed to compare temperature and pressure response to fuel acceleration during choked and unchoked operation. Figure 9 presents plots of fuel flow, compensated outlet temperature, and inlet static pressure for two approximately equal fuel acceleration rates at the simulated high-altitude condition to compare combustor response with and without the choke plates installed. It is noted that choked operation resulted in more rapid temperature and pressure response and higher final pressure. Figure 10 presents a similar comparison of data obtained at the simulated low-altitude condition. Choked operation again resulted in more rapid combustion response accompanied by higher final combustor static pressures.

Combustor Fuel Acceleration Limits at Two Simulated Altitude Conditions

The acceleration tests conducted at the simulated 50,000-foot altitude - 70 percent rated rotor speed condition are shown in figure 11(a) with acceleration rate plotted against the final fuel-air ratio. Different symbols are used to identify the combustor response characteristics observed. All accelerations shown in figure 11(a) were conducted from an initial fuel-air ratio of 0.0120, an initial combustion efficiency of 69 percent, and an outlet temperature of 700° F. An acceleration limit curve faired through data points representing limits of successful acceleration indicates the transition region between successful acceleration and blow-out or quench-out. The steady-state rich blow-out limit is included in figure 11(a) for comparison. It is noted that as the final fuel-air ratio increased and approached the steady-state rich limit region, the limiting acceleration rate was decreased. The region between the almost vertical portion of the acceleration limit curve and the rich blow-out limit represents the transient combustion blow-out region; that is, during the acceleration some increase in temperature occurred before blow-out. The region above the horizontal portion of the acceleration limit curve represents combustion quench-out; flame blow-out occurred during the acceleration with no temperature rise being observed.

The indicated fuel flow overshoot for the data along the almost vertical portion of the acceleration limit curve was either negligible at the very low acceleration rates or did not exceed the steady-state rich blow-out limit; therefore, overshoot probably did not exert much influence on the position of the acceleration limit curve in this region. However, the indicated overshoot for the rapid acceleration rates in the region above the horizontal portion of the acceleration curve was excessive and always either reached or exceeded the steady-state rich limit. Thus, the horizontal portion of the acceleration limit curve might possibly be shifted upward to higher permissible acceleration rates if overshoot were eliminated.

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Data are presented in figure 11(a) for both choked and unchoked operation. The position of the acceleration limit curve was not affected by the presence of the choke plates. For rapid acceleration rates (that is, greater than 0.005) the entire fuel flow change was completed before the temperature and pressure began to rise following their initial decrease; thus the more favorable higher final pressures obtained with choked operation did not improve combustion stability during the fuel flow change.

The acceleration tests conducted at the simulated 25,000-foot altitude - 70 percent rated rotor speed condition are shown in figure 11(b) with acceleration rate plotted against the final fuel-air ratio. These accelerations were conducted from an initial fuel-air ratio of 0.0077, with an initial combustion efficiency of 98 percent and an outlet temperature of 675° F. A steady-state blow-out limit was not determined at this condition since the outlet temperature at blow-out would have been sufficiently high to cause damage to test instrumentation. In lieu of a steady-state blow-out limit, a maximum outlet temperature of 1600° to 1700° F was chosen to correspond approximately to the turbine-inlet temperature limit in current turbojet engines. No combustion blow-outs or quench-outs were obtained at this condition for acceleration rates as rapid as 0.400; the capacity of the fuel system used did not permit more rapid acceleration at this low-altitude condition. The acceleration limit curve obtained at the high-altitude (50,000 ft) condition is included in figure 11(b) for comparison. It is noted that much more rapid acceleration rates could be tolerated by the combustion process at the low-altitude condition.

At the low-altitude condition the combustor-inlet static pressure increased from an initial value of 28 inches of mercury absolute to final values as high as 37 inches of mercury absolute (fig. 8). With the combustor installed in the full-scale engine, this rapid increase in combustor pressure would result in increased pressure ratio and possible compressor surge. As pointed out in reference 1, compressor surge in the full-scale engine limited acceleration at altitudes less than 35,000 feet.

Although no detailed studies of fuel deceleration were made, it was observed during the course of this investigation that, whenever successful acceleration was obtained to some high temperature level, deceleration did not incur blow-out. The decelerations always returned the fuel-air ratio to its initial value and never approached the steady-state lean blow-out limit.

Effect of Combustor Variables on Fuel Acceleration Limits

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The effects of initial combustor-outlet temperature, pressure, and velocity on acceleration limits were investigated at two inlet pressures (9.3 and 28 in. Hg abs) corresponding to the simulated 50,000- and 25,000-foot altitude conditions.

Effect of initial combustor-outlet temperature. - The quench-out phenomena observed at the simulated high-altitude condition suggest either the presence of local over-rich fuel-air mixtures or the lack of sufficient heat to vaporize and ignite the additional fuel being introduced. Preliminary studies were conducted in which the combustor-outlet temperature before acceleration was successively set at 500°, 850°, and 1000° F by changing the initial fuel-air ratio. Accelerations to a final fuel-air ratio giving an outlet temperature of 1600° F were conducted at a constant air velocity of 82 feet per second and a combustor-inlet pressure of 9.3 inches of mercury absolute. The effect of initial outlet temperature on the maximum acceleration rate is shown in figure 12, with the maximum acceleration rate for 1600° F final outlet temperature plotted against initial outlet temperature. It is noted that the maximum acceleration rate increased rapidly as the initial outlet temperature was increased.

The acceleration tests shown in figure 11(a) were conducted at an initial fuel-air ratio giving an initial outlet temperature of 700° F. Similar tests were conducted at the same conditions with an initial outlet temperature of 1000° F; the results are presented in figure 13. Only representative data points are shown in figure 13; the faired curve is based on results of additional tests not indicated. The acceleration limit curve for 1000° F initial outlet temperature is considerably higher than that for 700° F (included in fig. 14) over the range of final fuel-air ratios studied. No quench-out region is indicated on the acceleration limit curve for the 1000° F initial temperature; however, if more rapid accelerations had been obtained, quench-out might have occurred at some higher acceleration rate.

Figures 12 and 13 show that increasing the initial outlet temperature had a very beneficial influence on the acceleration limits at the simulated high-altitude condition. If it is considered that the increased initial outlet temperature improved acceleration by providing additional heat for vaporization of the incoming fuel, then the heat-release rate in terms of Btu per second may be a more important parameter controlling

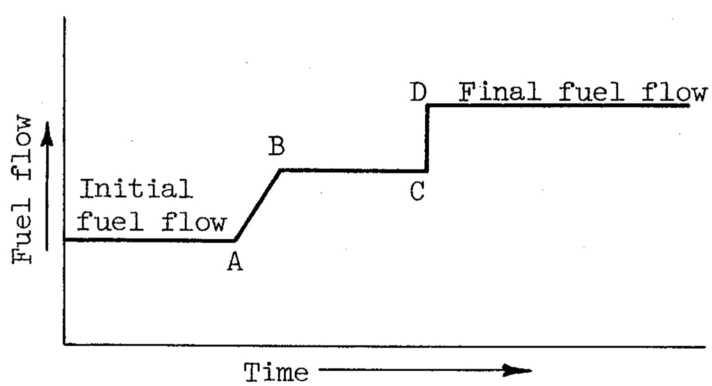
acceleration. Acceleration tests were conducted at the higher-pressure condition (28 in. Hg abs) with the initial heat-release rate (137 Btu/sec) the same as in the low-pressure tests (700° F, fig. 11(a)). At the higher-pressure condition, the required initial outlet temperature was 290° F. The observed combustion efficiency (69 percent) was the same as that observed in the previous low-pressure test; therefore the initial fuel flow in both cases was identical. The results of these fuel acceleration tests are shown in figure 14. It is noted that for the range of
3062 final fuel-air ratios investigated, only a quench-out limit was determined at the higher-pressure condition. The quench-out limit compares favorably with the quench-out limit obtained at the higher-altitude (lower-pressure) condition. Higher final fuel-air ratios than those indicated in figure 14 were not investigated because the resulting higher outlet temperatures would have exceeded the safe limit of the instrumentation. The coincidence of the two acceleration curves in figure 14 indicates the possible importance of initial heat-release rate in controlling acceleration limits over a range of operating conditions.

Effect of initial combustor-inlet pressure on acceleration limits. - When initial heat-release rate and air velocity were held constant and inlet air pressure was increased from 9.3 to 28 inches of mercury absolute, the acceleration quench-out limits were not increased (fig. 14). It would appear then, that pressure is important only because it influences the steady-state rich blow-out limit; thus, as pressure is decreased, steady-state blow-out fuel-air ratio and outlet temperature are generally decreased. Tests at 9.3 inches of mercury absolute show that as the final fuel-air ratio after acceleration approaches the steady-state limit, acceleration rates must be reduced considerably to avoid blow-out.

Effect of combustor air velocity. - Acceleration tests were conducted over a range of combustor air velocities at 9.3 and 28 inches of mercury absolute. Figure 15 presents the observed variation in maximum acceleration rate with air velocity. The accelerations were conducted to a final outlet temperature of 1600° F; the initial heat-release rate was held constant at 137 Btu per second. The data for 9.3 inches of mercury absolute were obtained at a final fuel-air ratio of approximately 0.030, which is very near the steady-state blow-out range. Thus, the maximum acceleration rates presented are much lower than those obtained at lower final fuel-air ratios at the same velocity and initial heat-release rate, (i.e., at $(f/a)_2 = 0.0268$, the maximum acceleration would be approximately 0.052, fig. 11(a)). Therefore these data should not be used to compare the maximum acceleration rates obtainable at both altitude conditions. However, the data presented for 9.3 inches of mercury absolute indicate that as velocity increased, maximum acceleration decreased; the data obtained at 28 inches of mercury absolute show that as velocity increased, maximum acceleration rate increased. These data suggest the existence of an optimum velocity for each set of combustor operating conditions. It is possible that such an optimum velocity may also be influenced by fuel-spray characteristics such as cone angle, penetration, and atomization.

Effect of Successive-Step Fuel Acceleration on Acceleration Limits at High-Altitude Conditions

A comparison of the minimum time required to accelerate from initial
outlet temperatures of 700° and 1000° F to various final fuel-air ratios
is presented in figure 16. The time for acceleration was computed from
the acceleration limit curves for 700° and 1000° F initial outlet temper-
atures at the simulated high-altitude condition (figs. 11(a) and 13).
It is noted that from 0.3 to 10 seconds were required for acceleration
from the low initial outlet temperature to final fuel-air ratios near the 3062
steady-state blow-out limit. It is also noted that the higher initial
outlet temperature required much shorter time for acceleration to equiva-
lent final fuel-air ratios. It is possible that the time required for
acceleration under critical operating conditions could be reduced by a
programmed acceleration providing for an increase in the acceleration
rate as higher values of fuel-air ratio and outlet temperature are ob-
tained. A fuel acceleration of this type, composed of two steps, is il-
lustrated in the following sketch:



The initial acceleration AB is followed by a delay BC, which allows the temperature to recover from the initial decrease to reach some higher value. The final fuel step may next be imposed very rapidly because of the now increased initial temperature.

The time necessary for the outlet temperature to recover from its initial decrease was assumed to be constant at 1.85 seconds. Data presented in figures 6 and 7 indicated this assumption to be approximately true. The final step was assumed to be imposed instantaneously. It is noted from figure 16 that a calculated successive-step acceleration with a constant acceleration time of 1.85 seconds would provide faster acceleration rates than the single-step acceleration for final fuel-air ratios beyond 0.0304. At final fuel-air ratios less than 0.0304, however, single-step acceleration is faster since the time required for single-step acceleration is reduced as final fuel-air ratio is reduced, whereas the time required for successive-step acceleration remains constant. Thus, successive-step fuel acceleration would be advantageous only for operation near the steady-state rich blow-out limit and at low combustor pressures.

VISUAL AND PHOTOGRAPHIC OBSERVATIONS

Visual observations as well as high-speed motion pictures were made of the combustion during rapid acceleration. At the low initial fuel-air ratios the burning took place entirely in the primary zone of the combustor and the flame was yellowish-blue in color. During fuel acceleration, the burning zone occupied the full length of the combustor and the flame turned a nonluminous blue color. This nonluminosity made it virtually impossible to obtain clear motion pictures of combustion during acceleration.

Additional visual and high-speed motion picture studies were made of the fuel sprays during fuel acceleration. For these studies the combustor was removed so that the nozzle spray could be more easily observed. Nozzle pressure drop and fuel flows simulated those used in the acceleration test program. The spray studies revealed that the high-speed instrumentation indicated an increase in fuel flow prior to the time at which an increase in fuel flow was observed. Analysis of the flow conditions indicated that this may possibly have been due to recirculation of fuel within the duplex nozzle. The period during which the recirculation took place was very short (of the order of 0.01 to 0.03 sec), and therefore possibly did not affect the acceleration process in the combustor.

CONCLUDING REMARKS

An investigation of transient combustion characteristics was conducted in a single tubular combustor at two simulated altitude - rotor speed conditions, 25,000 feet - 70 percent rated and 50,000 feet - 70 percent rated. It was determined that the combustion may follow one of three paths as the result of a rapid increase in fuel flow:

1. Successful acceleration with sustained burning at higher levels of temperature, pressure, and fuel-air ratio

2. Successful acceleration to higher levels of temperature, pressure, and fuel-air ratio momentarily, followed by combustion blow-out if the final conditions approached the steady-state rich blow-out limit

3. Immediate combustion blow-out during very rapid rates of increase of fuel flow

The results indicated that as the rate of change of fuel flow (acceleration rate) was increased, blow-out occurred at lower final fuel-air ratios and that the control of fuel acceleration rates became very critical at high-altitude operating conditions where the steady-state rich blow-out fuel-air ratios and outlet temperatures are reduced. For succesful acceleration, the final fuel-air ratio after acceleration must always be somewhat below the steady-state rich blow-out limit.

A study of the individual effects of combustor-outlet temperature prior to acceleration, combustor-inlet static pressure, and combustor air velocity indicated that: 3062

1. As initial outlet temperature was increased, the acceleration limits were increased

2. For the same initial heat-release rate, inlet static pressure affected maximum acceleration rates only by affecting the steady-state blow-out limits of the combustor

3. An optimum air velocity with respect to acceleration existed for each different operating condition.

Tests conducted at different altitude conditions but similar heat-release rates indicated similar acceleration limits and suggested that the initial heat-release rate may be an important parameter controlling acceleration.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 3, 1953

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TABLE I. - HIGH- AND LOW-ALTITUDE ACCELERATION DATA FROM SINGLE TUBULAR COMBUSTOR

[Simulated rotor speed, 70 percent rated; reference velocity, 82 ft/sec]

(a) Simulated altitude, 50,000 feet; inlet static pressure, 9.3 inches of mercury absolute; air flow, 0.9 pound per second; initial fuel-air ratio, $(f/a)_1$, 0.0120; initial outlet temperature, 700° F

Run number	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Inlet and outlet choke plates	Combustor response	Run number	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Inlet and outlet choke plates	Combustor response
1	0.0370	0.18	0.139	Out	Quench-out	31	0.0358	0.52	0.0458	Out	Quench-out
2	.0370	.43	.0581			32	.0355	.64	.0368		Blow-out
3	.0355	.60	.0384			33	.0334	.56	.0382		Blow-out
4	.0355	.72	.0320			34	.0334	.42	.0510		Quench-out
5	.0364	1.00	.0244		Blow-out	35	.0231	.14	.0794		Quench-out
6	.0342	1.16	.0191			36	.0231	.24	.0462		Successful
7	.0322	.88	.0229			37	.0231	.88	.0126		Successful
8	.0309	1.40	.0135			38	.0244	.14	.0886		Quench-out
9	.0309	3.08	.00614		Successful	39	.0376	3.76	.00675		Blow-out
10	.0327	.28	.074		Quench-out	40	.0321	6.00	.00335		Blow-out
11	.0293	.168	.103		Quench-out	61	.0291	.60	.0285	In	Blow-out
12	.0293	2.0	.00865		Successful	62	.0290	.80	.0212		Successful
13	.0299	1.0	.0179		Blow-out	63	.0290	.26	.0654		Quench-out
14	.0293	.92	.0188		Successful	64	.0280	1.10	.0145		Successful
15	.0293	.90	.0192		Successful	65	.0287	2.70	.0062		
16	.0287	.28	.0596		Quench-out	66	.0287	.36	.0465		
17	.0268	.26	.051		Quench-out	67	.0280	6.00	.00267		
18	.0268	.56	.0264		Successful	68	.0337	5.40	.004		Blow-out
19	.0259	.46	.0302		Successful	69	.0318	6.20	.00319		Successful
20	.0259	.28	.0496		Quench-out	70	.0327	1.30	.0159		Blow-out
21	.0259	.50	.0278		Successful	71	.0312	1.00	.0192		
22	.0259	.72	.0193			72	.0321	4.10	.0049		
23	.0253	1.0	.0133			73	.0315	8.40	.00232		
24	.0256	1.56	.00873			74	.0306	8.00	.00232		Successful
25	0268	5.5	.00269			75	.0315	3.50	.00551		Blow-out
26	.0309	6.0	.00315		Blow-out	76	.0302	3.15	.00518		Successful
27	.0336	9.4	.00230			77	.0308	1.35	.0139		Blow-out
28	.0336	3.6	.0060			78	.0250	.132	.0985		Quench-out
29	.0336	1.0	.0216			79	.0244	.20	.0620		Successful
30	.0342	.8	.0278								

TABLE I. - Concluded. HIGH- AND LOW-ALTITUDE ACCELERATION DATA FROM SINGLE TUBULAR COMBUSTOR

[Simulated rotor speed, 70 percent rated; reference velocity, 82 ft/sec]

(b) Simulated altitude, 25,000 feet; inlet static pressure, 28.0 inches of mercury absolute; air flow, 2.7 pounds per second; initial fuel-air ratio, $(f/a)_1$, 0.0077; initial outlet temperature, 675° F

Run number	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Inlet and outlet choke plates	Combustor response
120	0.01582	0.36	0.0225	In	Successful
121	.01582	.04	.205	↓	↓
122	.01582	.11	.0748	↓	↓
123	.01582	.15	.0514	↓	↓
124	.01582	.90	.00915	↓	↓
125	.0201	.88	.0141	↓	↓
126	.0200	.22	.0563	↓	↓
127	.0200	.14	.0885	↓	↓
128	.0201	.04	.313	↓	↓
129	.0236	.04	.400	↓	↓
130	.0236	.12	.1325	↓	↓
131	.0233	.26	.060	↓	↓

TABLE II. - VARIABLE INITIAL COMBUSTOR-OUTLET TEMPERATURE DATA FROM SINGLE TUBULAR COMBUSTOR

[Simulated altitude, 50,000 ft; inlet static pressure, 9.3 in. Hg abs; air flow, 0.9 lb/sec; reference velocity, 82 ft/sec; final outlet temperature, 1600° F]

Run number	Initial fuel-air ratio, $(f/a)_1$	Initial outlet temperature, °F	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Inlet and outlet choke plates	Combustor response
100	0.0193	1000	0.0296	0.04	0.257	In	Successful
101	↓	↓	.0318	.04	.312	↓	Blow-out
102	↓	↓	.0308	.09	.128	↓	Blow-out
103	↓	↓	.0299	.35	.034	↓	Successful
104	↓	↓	.0308	.36	.0321	↓	Successful
	.0077	500	------	----	.0085	↓	↓
	.0043	850	------	----	.170	↓	↓

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TABLE III. - REDUCED INITIAL OUTLET TEMPERATURE DATA FROM SINGLE TUBULAR COMBUSTOR

[Simulated altitude, 25,000 ft; simulated rotor speed, 70 percent rated, inlet static pressure, 28.0 in. Hg abs; air flow, 2.7 lb/sec reference velocity, 82 ft/sec; initial fuel-air ratio, $(f/a)_1$, 0.004; initial outlet temperature, 290° F; inlet and outlet choke plates in.]

Run number	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Combustor response
157	0.0241	0.85	0.0241	Successful
158	.0239	.5	.041	↓
159	.0239	.32	.064	↓
160	.0243	.28	.0732	Quench-out
161	.0212	.26	.0685	↓
162	.0212	.36	.0495	↓
163	.0205	.8	.0214	Successful
164	.0150	.5	.0231	↓
165	.0150	.35	.033	↓
166	.0151	.28	.042	Quench-out

TABLE IV. - VARIABLE COMBUSTOR REFERENCE VELOCITY DATA FROM SINGLE TUBULAR COMBUSTOR

[Inlet and outlet choke plates in.]

Run number	Inlet static pressure, in. Hg abs	Air flow lb/sec	Reference velocity, ft/sec	Initial fuel-air ratio, $(f/a)_1$	Initial outlet temperature, °F	Final fuel-air ratio, $(f/a)_2$	Time for acceleration, t, sec	Acceleration rate, $\frac{(f/a)_2-(f/a)_1}{t}$	Combustor response
172	28.0	3.26	100	0.00272	265	0.0218	0.16	0.119	Quench-out
173	↓	3.26	100	.00272	265	.0218	.20	.095	Successful
174	↓	2.02	60	.0041	375	.01565	.27	.073	Quench-out
175	↓	2.02	60	.0041	375	.01495	.40	.0475	Successful
176	9.3	.68	60	.00533	845	.01066	.24	.0222	Successful

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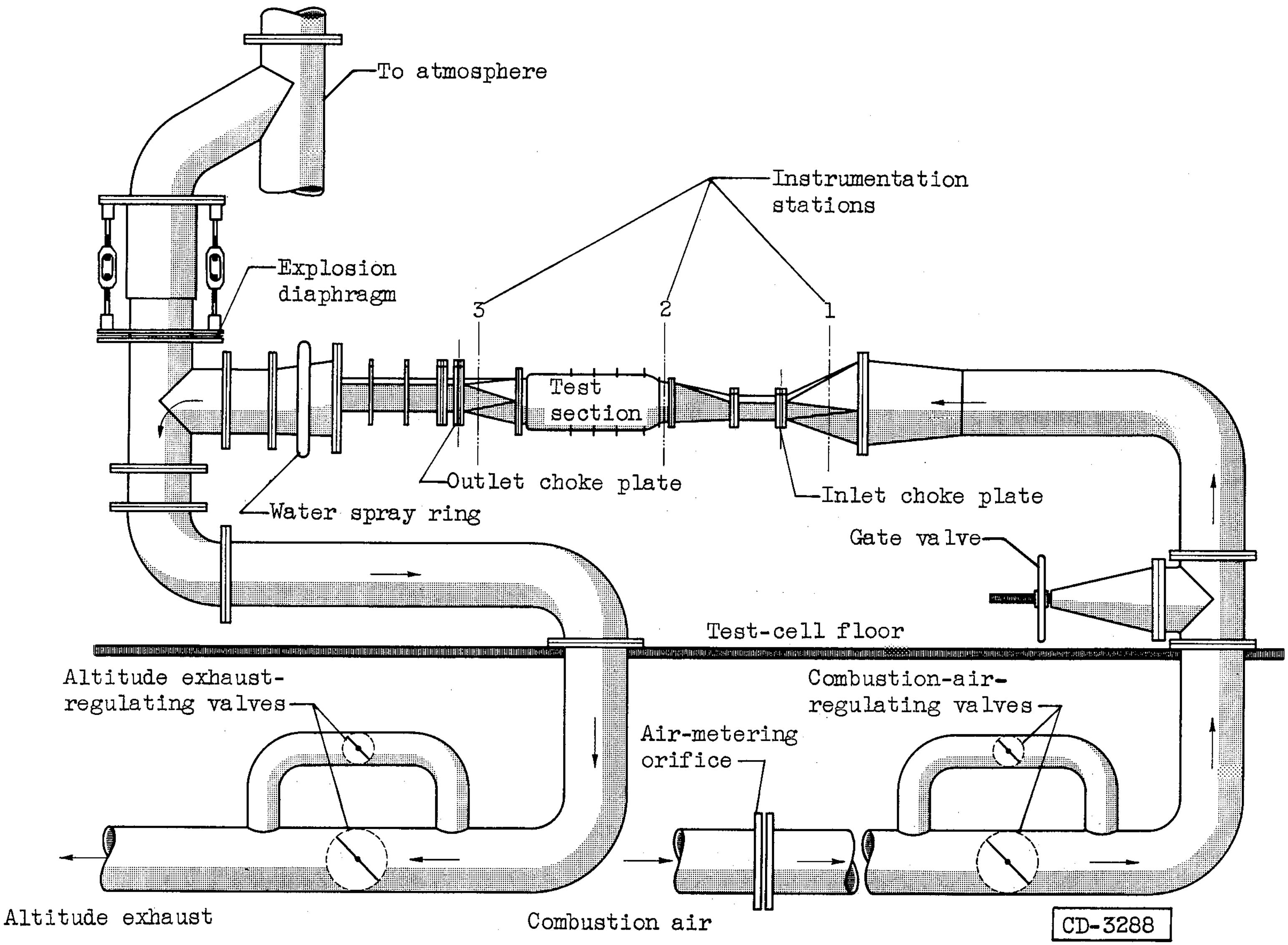


Figure 1. - Diagrammatic sketch of single tubular combustor installation.

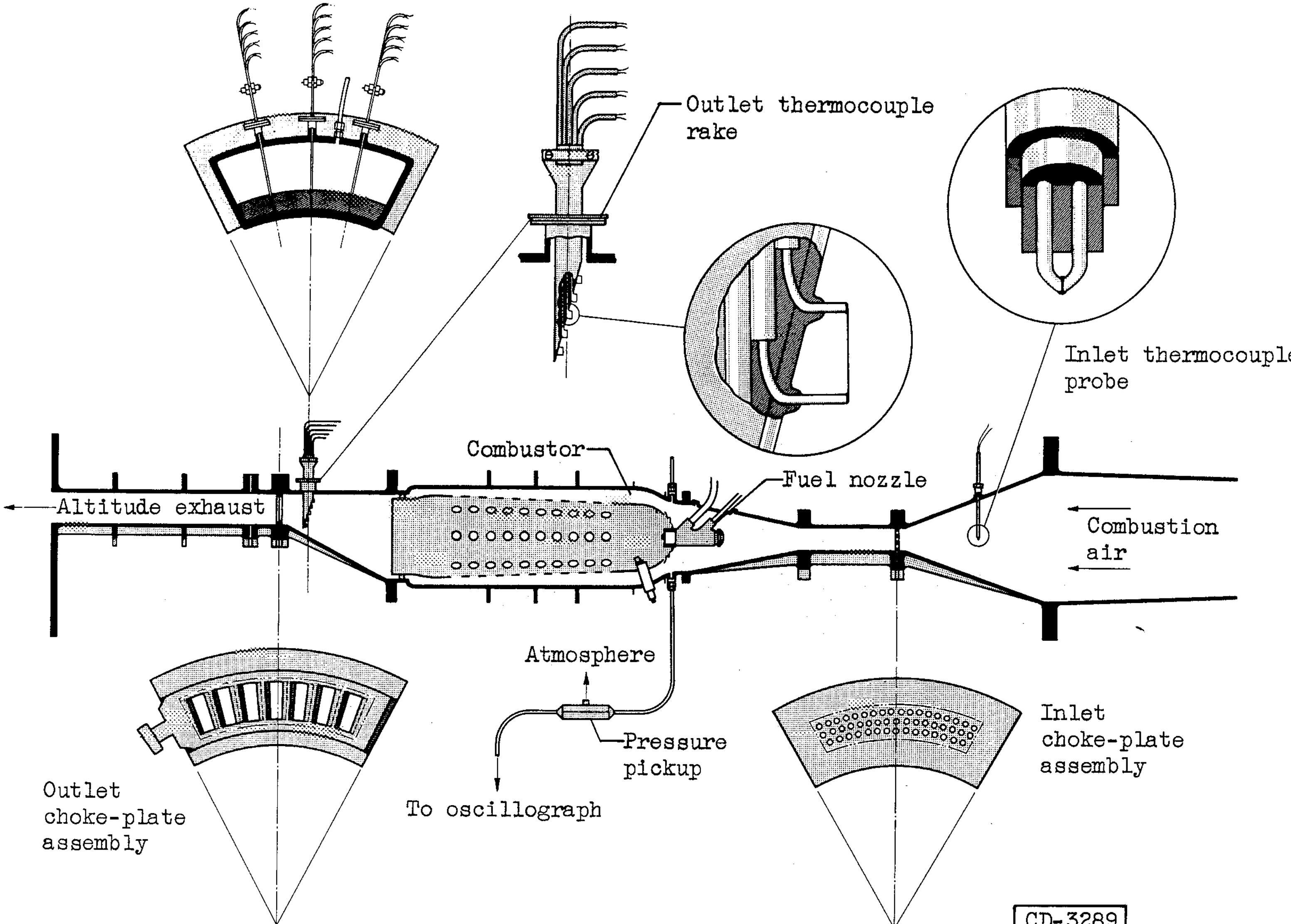


Figure 2. - Instrumentation for acceleration studies.

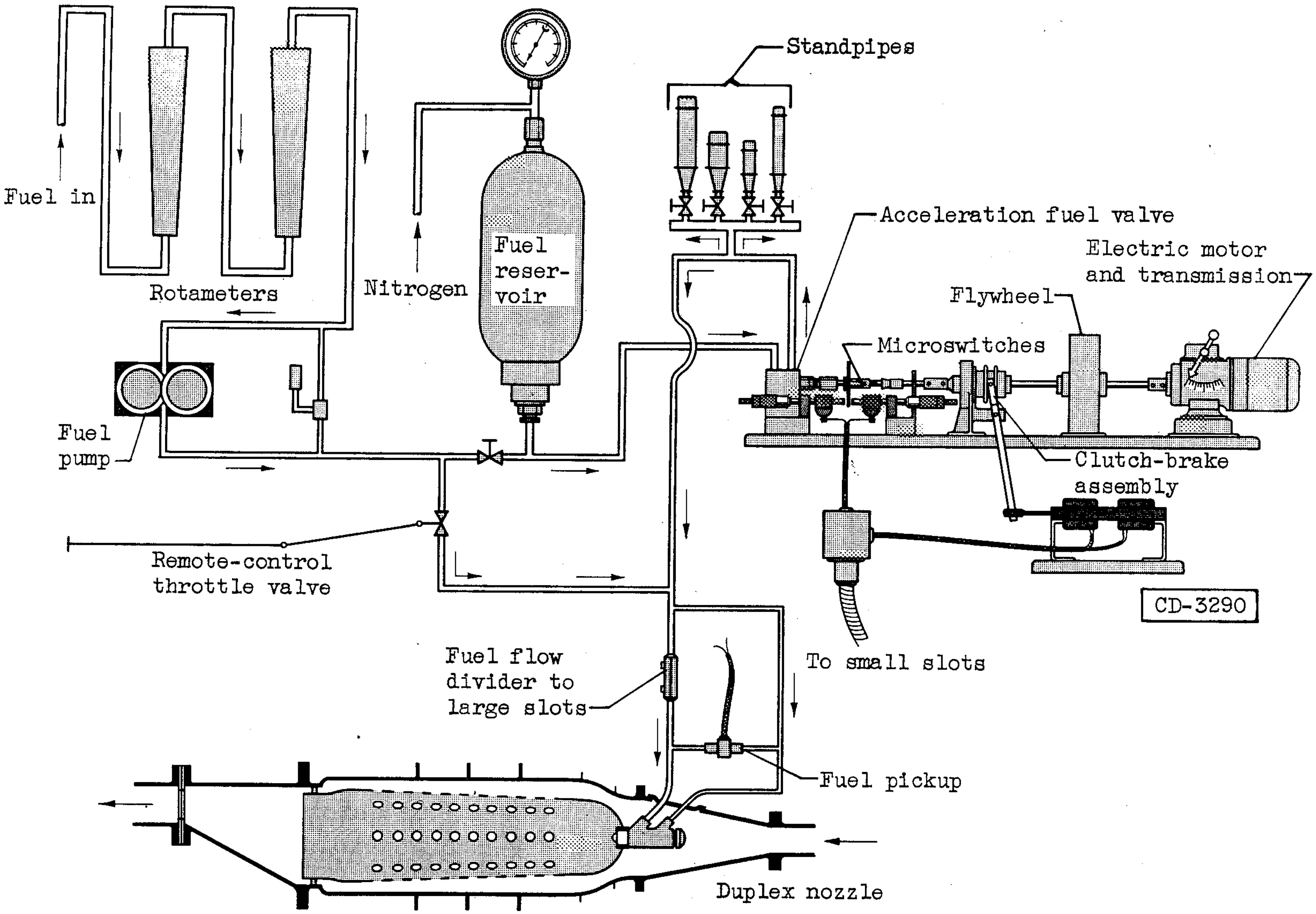
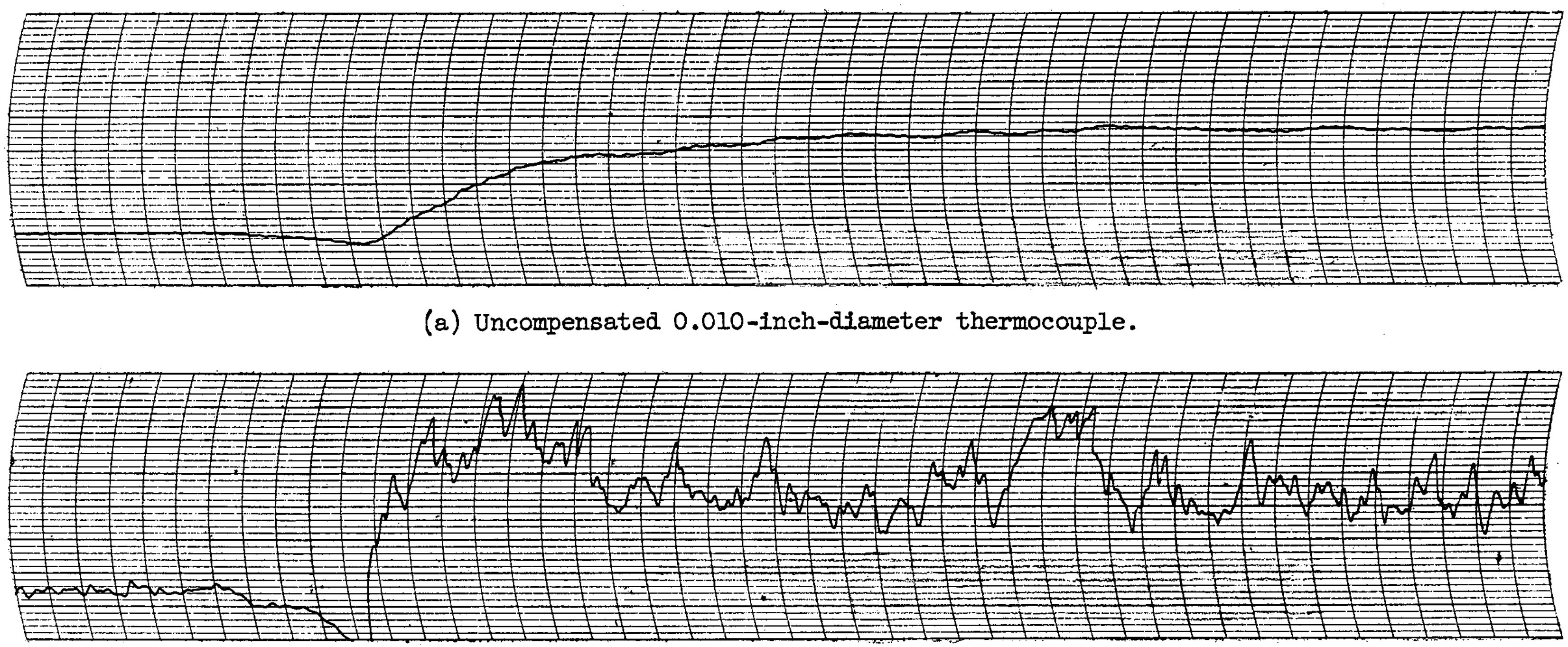


Figure 3. - Schematic diagram of fuel system used for acceleration tests in single combustor.



(a) Uncompensated 0.010-inch-diameter thermocouple.

(b) Compensated 0.010-inch-diameter thermocouple.

Figure 4. - Effect of thermal lag compensation on response of single bare-junction chromel-alumel thermocouple to equal rates of flowing gas temperature change.

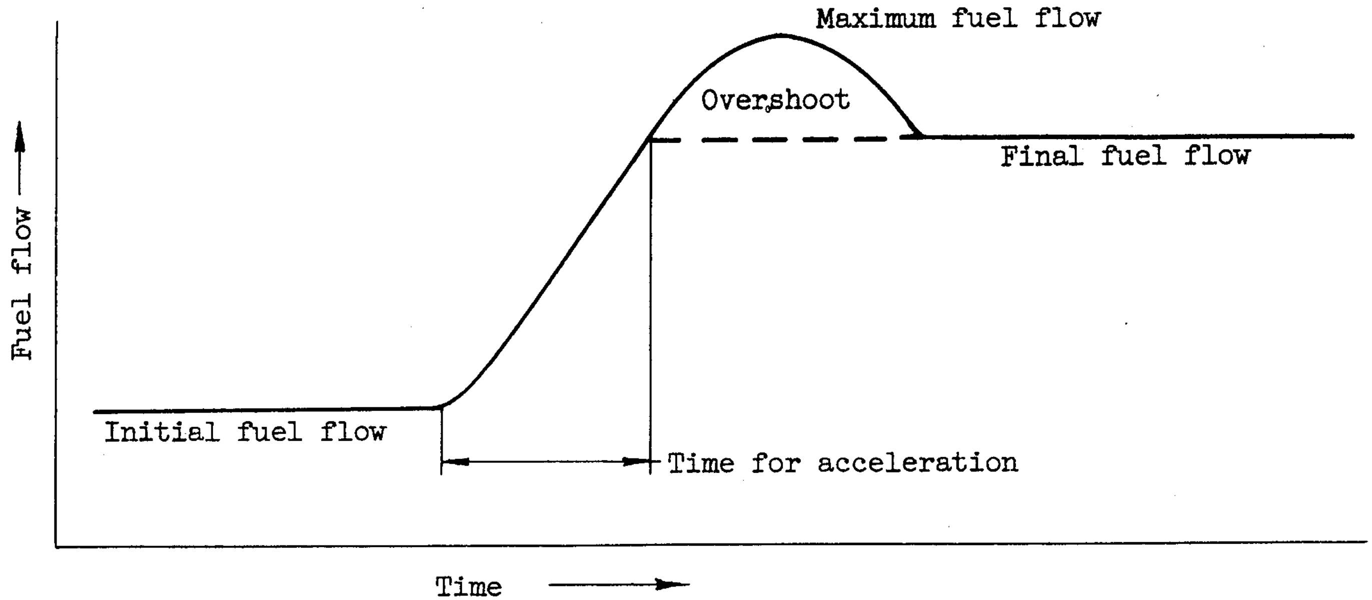


Figure 5. - Typical oscillograph trace of a fuel acceleration (ramp).

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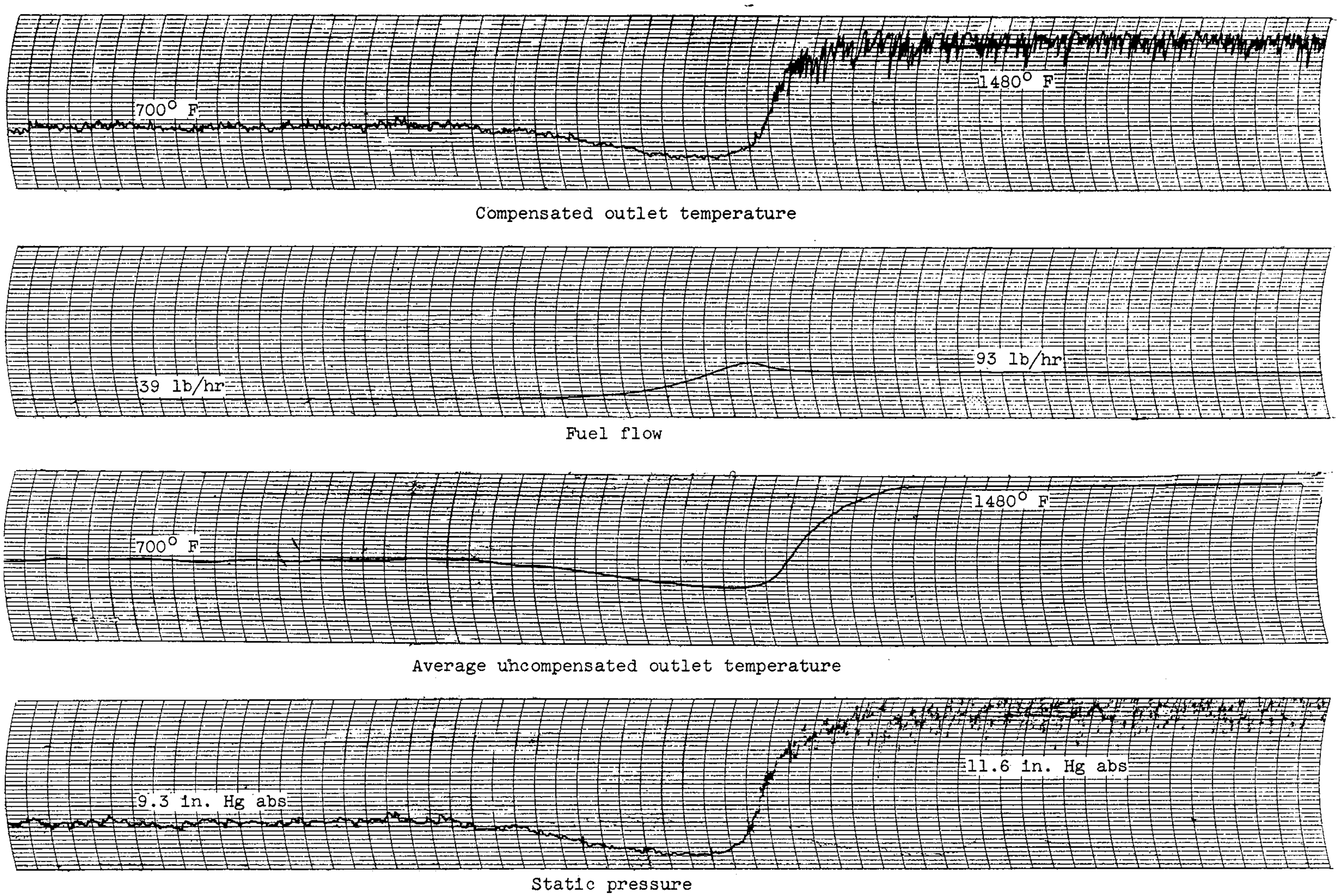

(a) Successful acceleration. Chart speed, 5 divisions per second; run 65.

Figure 6. - Typical oscillograph trace of combustor variables during fuel acceleration. Altitude, 50,000 feet; rated rotor speed, 70 percent.

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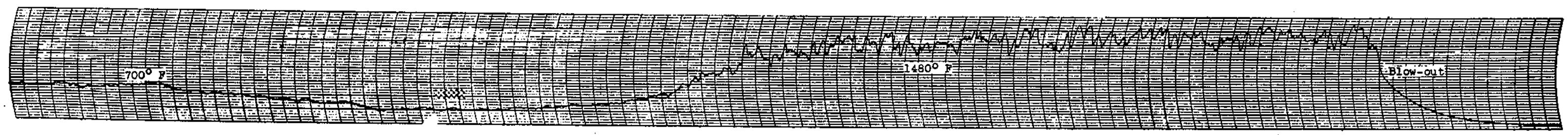
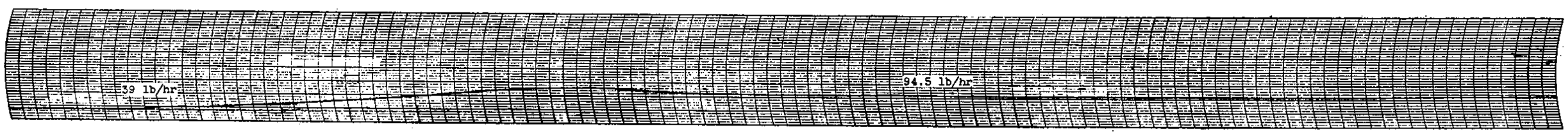
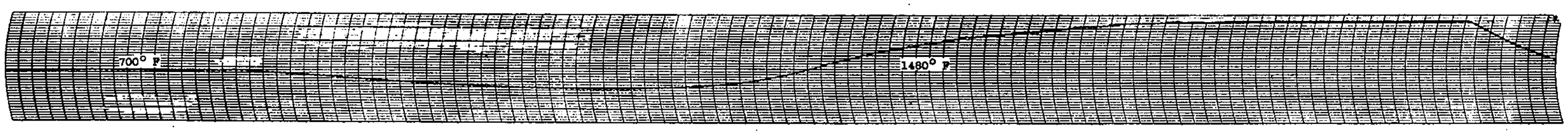


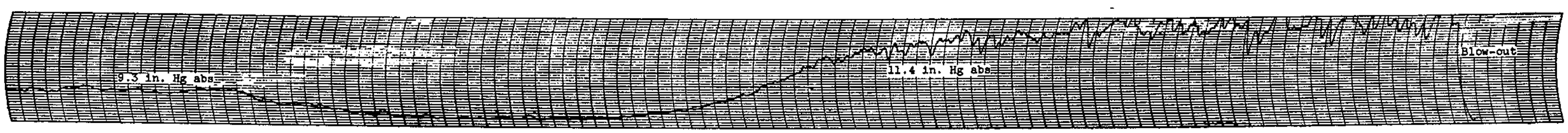
Compensated outlet temperature



Fuel flow



Average uncompensated outlet temperature



Static pressure

(b) Blow-out. Chart speed, 25 divisions per second; run 61.

Figure 6. - Continued. Typical oscillograph trace of combustor variables during fuel acceleration. Altitude, 50,000 feet; rated rotor speed, 70 percent.

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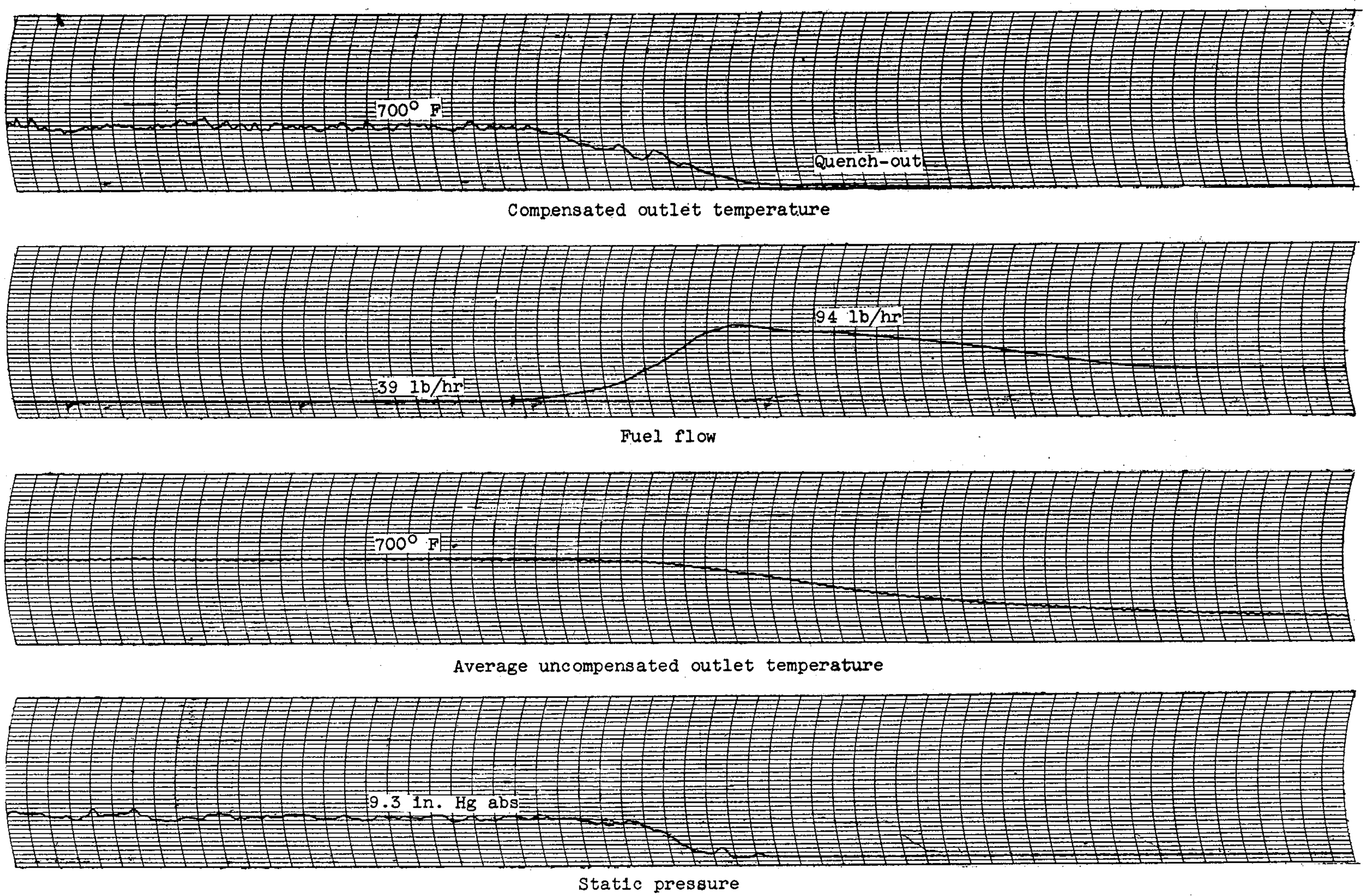

(c) Quench-out. Chart speed, 25 divisions per second; run 63.

Figure 6. - Concluded. Typical oscillograph trace of combustor variables during fuel acceleration. Altitude, 50,000 feet; rated rotor speed, 70 percent.

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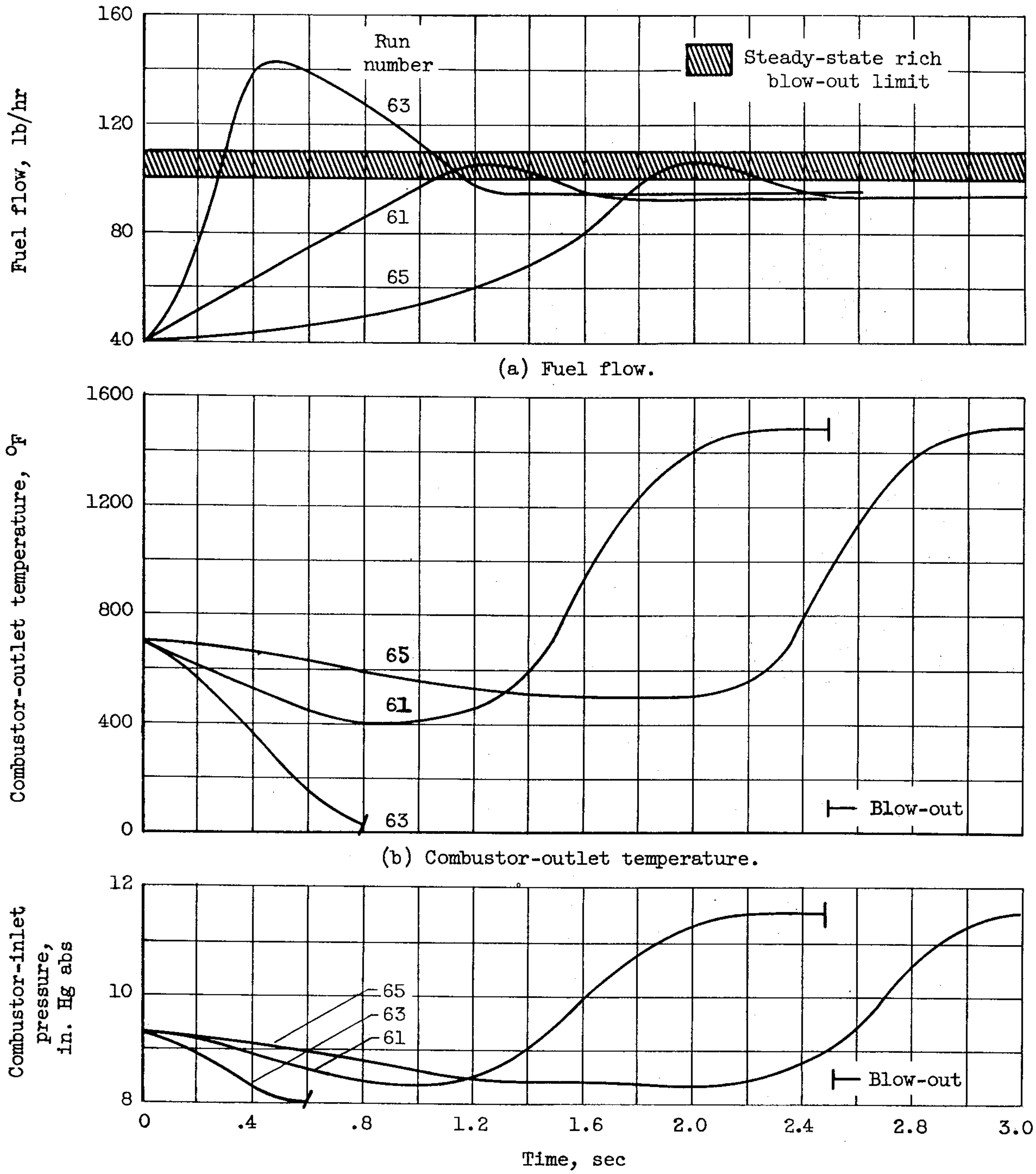

(a) Fuel flow.

(b) Combustor-outlet temperature.

(c) Inlet static pressure.

Figure 7. - Effect of varying fuel acceleration rates on combustor-outlet temperature and inlet static pressure. Altitude, 50,000 feet; rotor speed, 70 percent rated.

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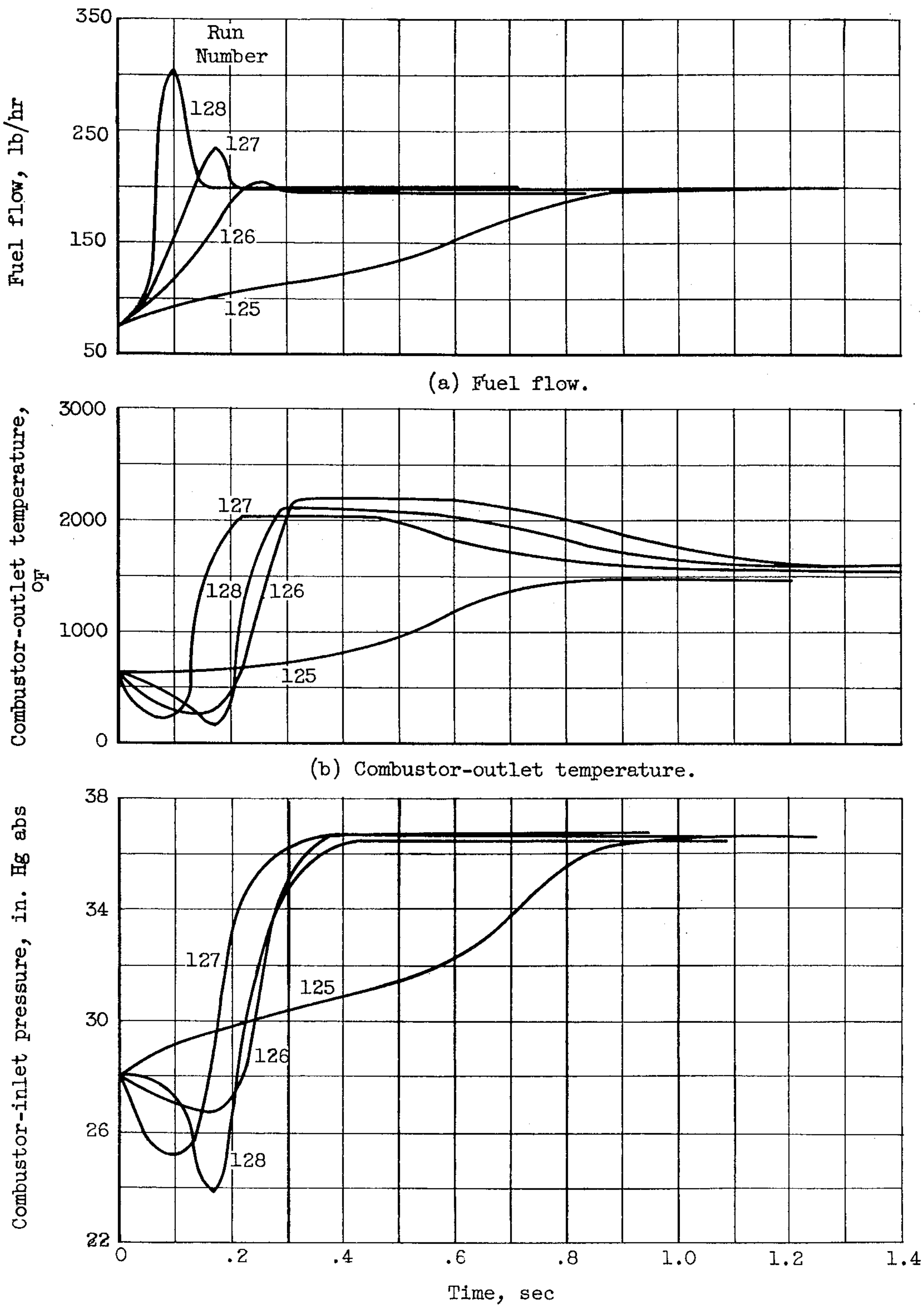
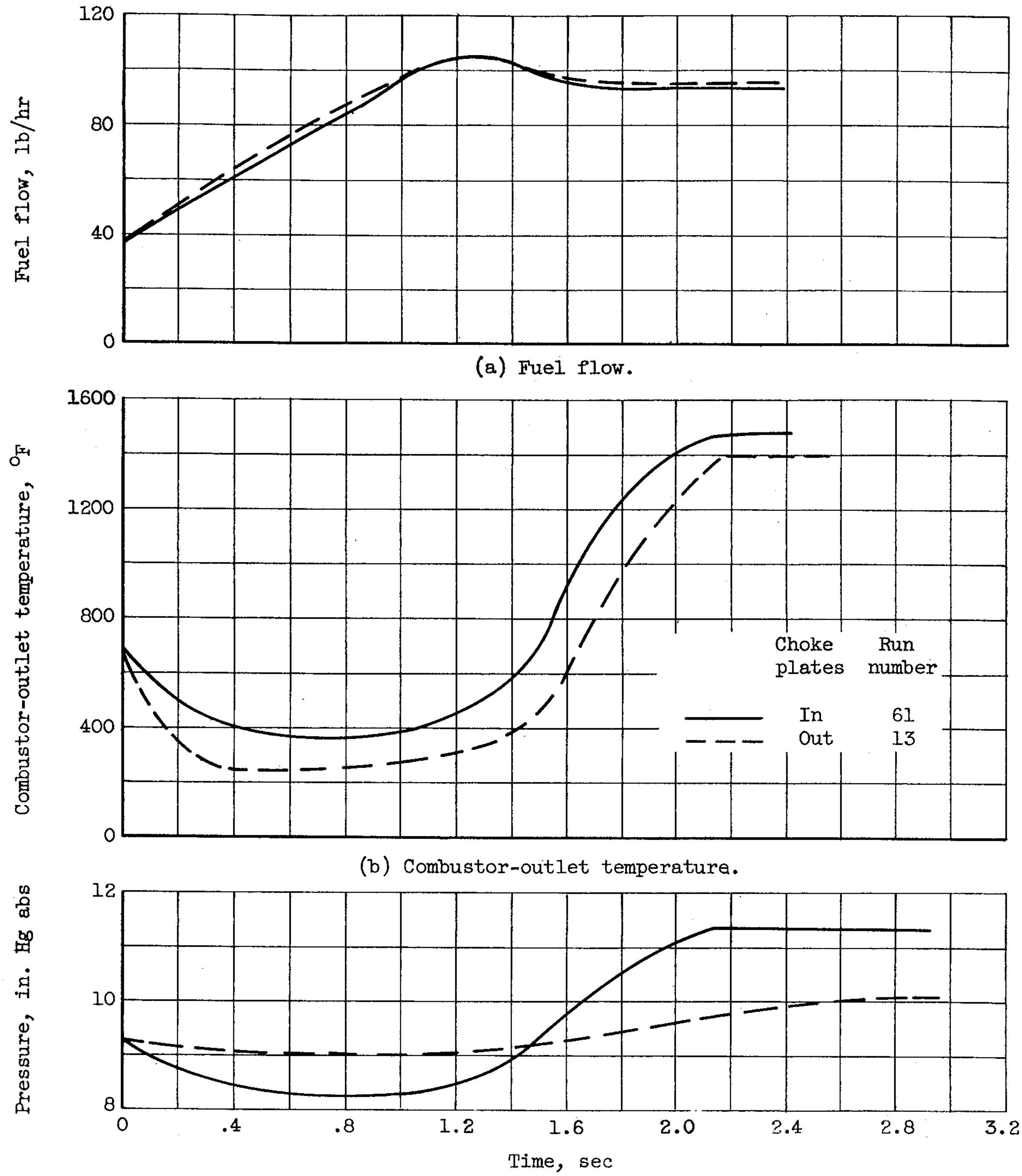


(a) Fuel flow.

(b) Combustor-outlet temperature.

(c) Inlet static pressure.

Figure 8. - Effect of varying fuel acceleration rates on combustor-outlet temperature and inlet static pressure. Altitude, 25,000 feet; rotor speed, 70 percent rated.

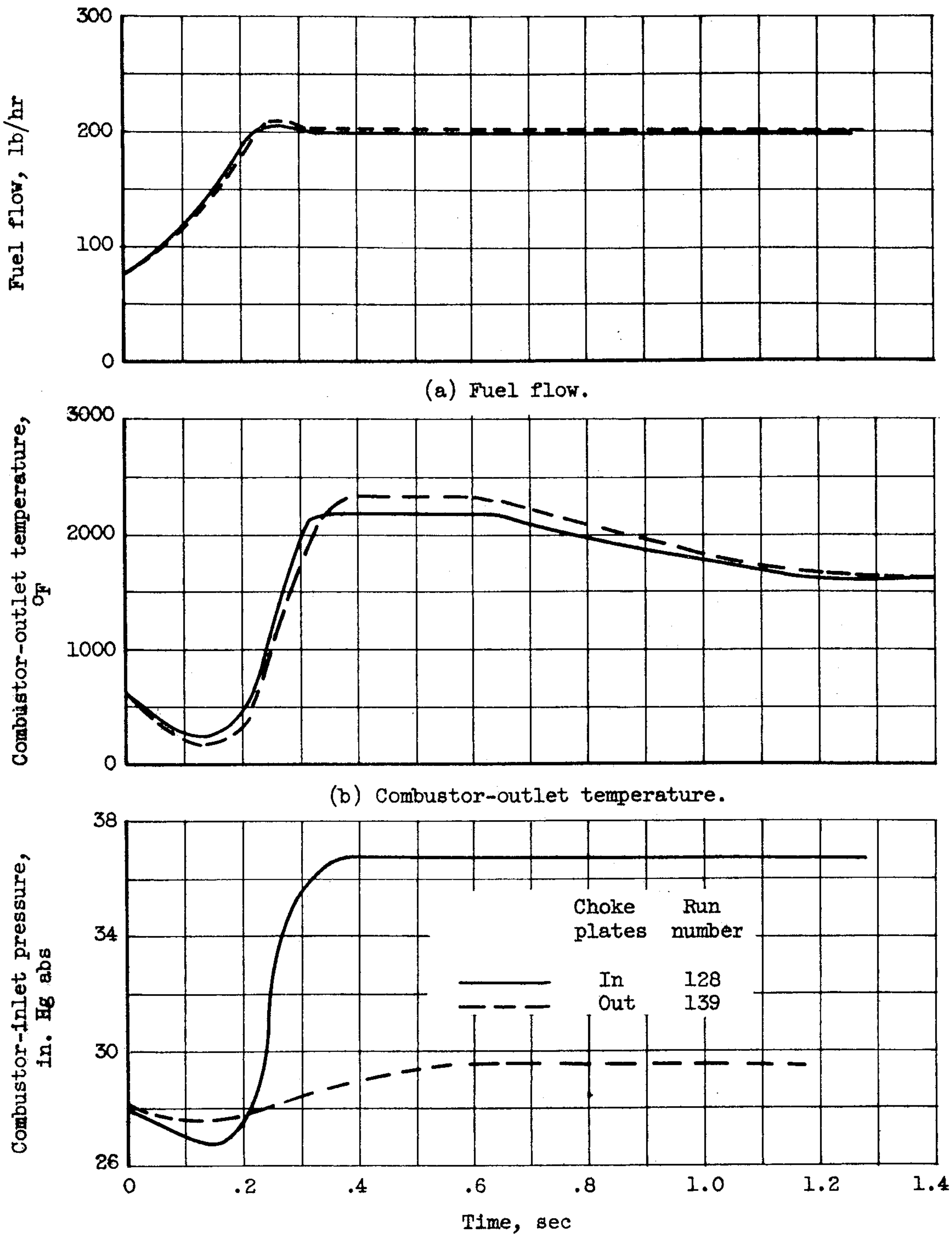


(a) Fuel flow.

(b) Combustor-outlet temperature.

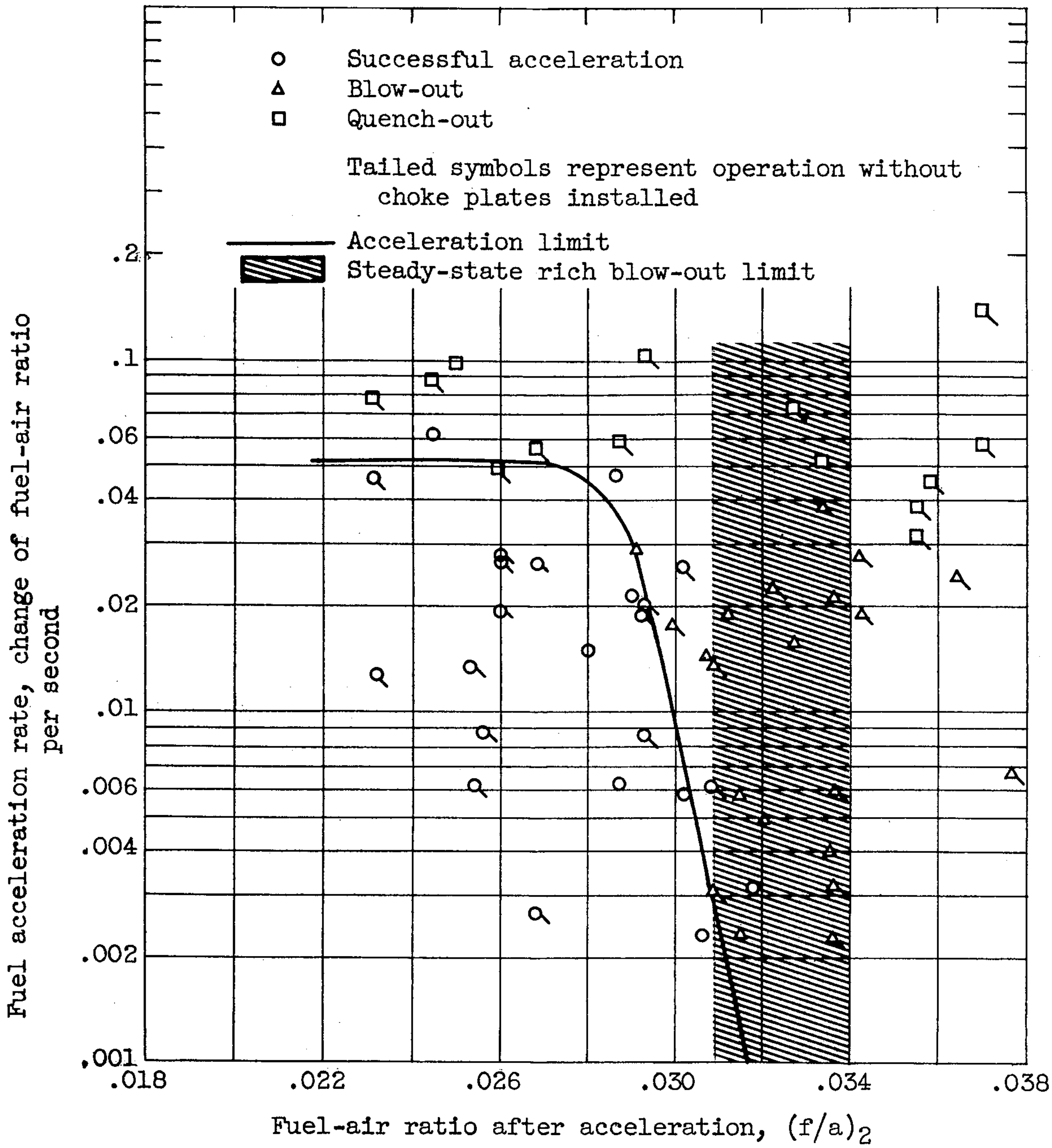
(c) Inlet static pressure.

Figure 9. - Comparison of combustor-outlet temperature and inlet static pressure response to fuel acceleration with and without inlet and outlet choke plates installed. Altitude, 50,000 feet; rotor speed, 70 percent rated.



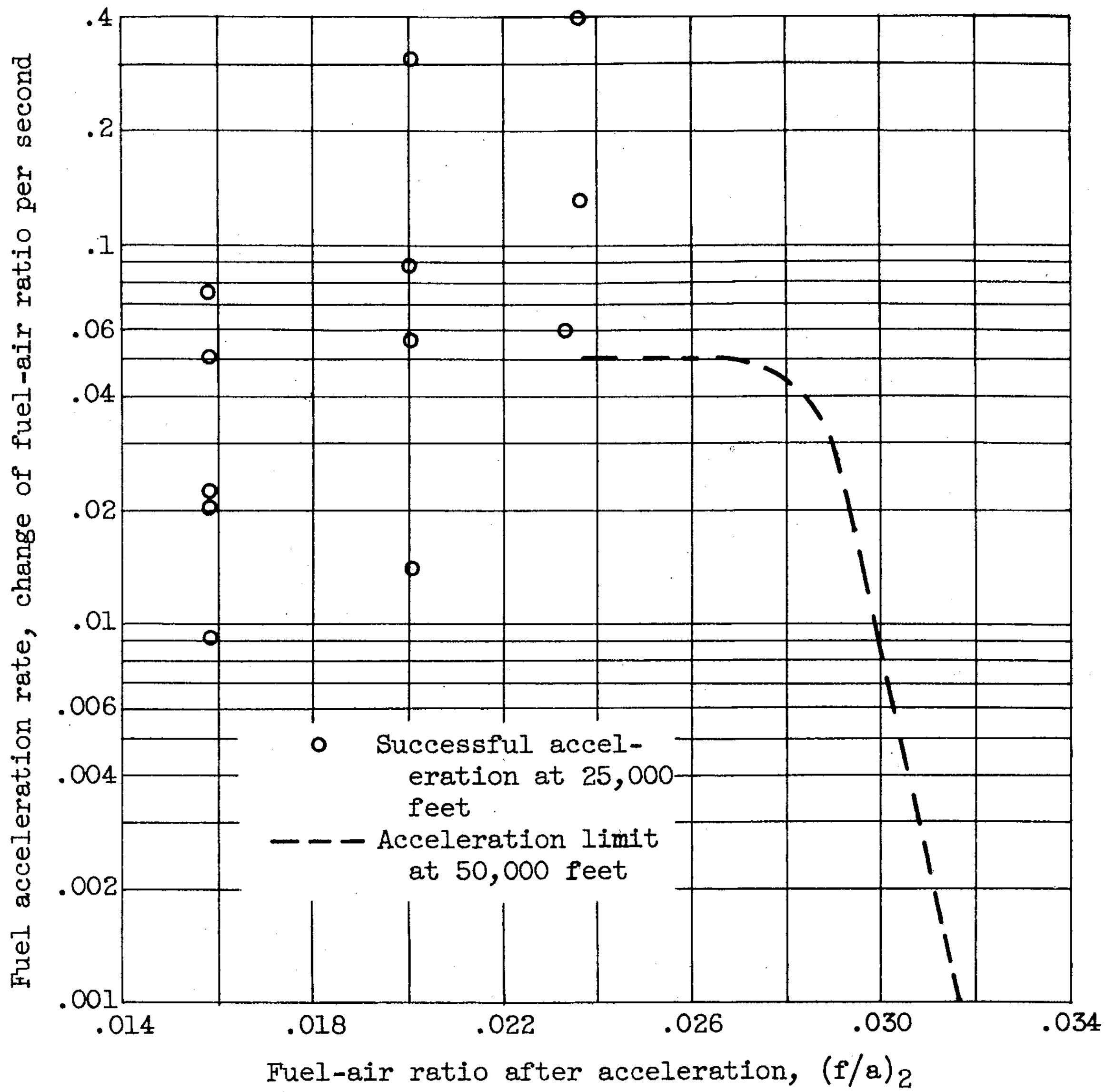
(c) Inlet static pressure.

Figure 10. - Comparison of combustor-outlet temperature and inlet static-pressure response to fuel acceleration with and without inlet and outlet choke plates installed. Altitude, 25,000 feet; rotor speed, 70 percent rated.



(a) Simulated altitude, 50,000 feet.

Figure 11. - Combustor fuel acceleration limits at two simulated altitudes. Rotor speed, 70 percent rated.



(b) Simulated altitude, 25,000 feet.

Figure 11. - Concluded. Combustor fuel acceleration limits at two simulated altitudes. Rotor speed, 70 percent rated.

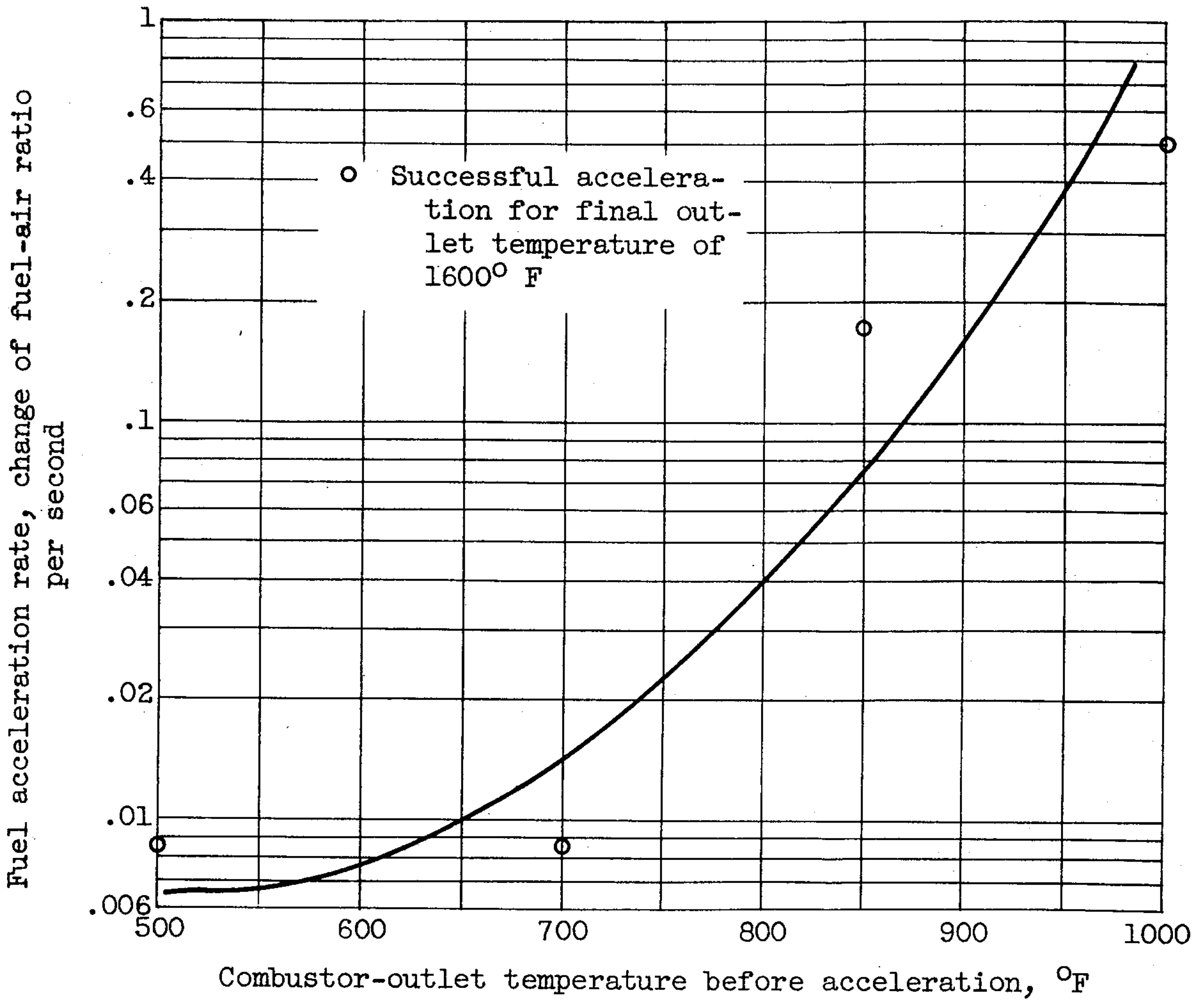


Figure 12. - Effect of combustor-outlet temperature before acceleration on maximum acceleration rate. Air flow, 0.9 pounds per second; velocity, 82 feet per second; pressure, 9.3 inches of mercury absolute; final outlet temperature, 1600° F.

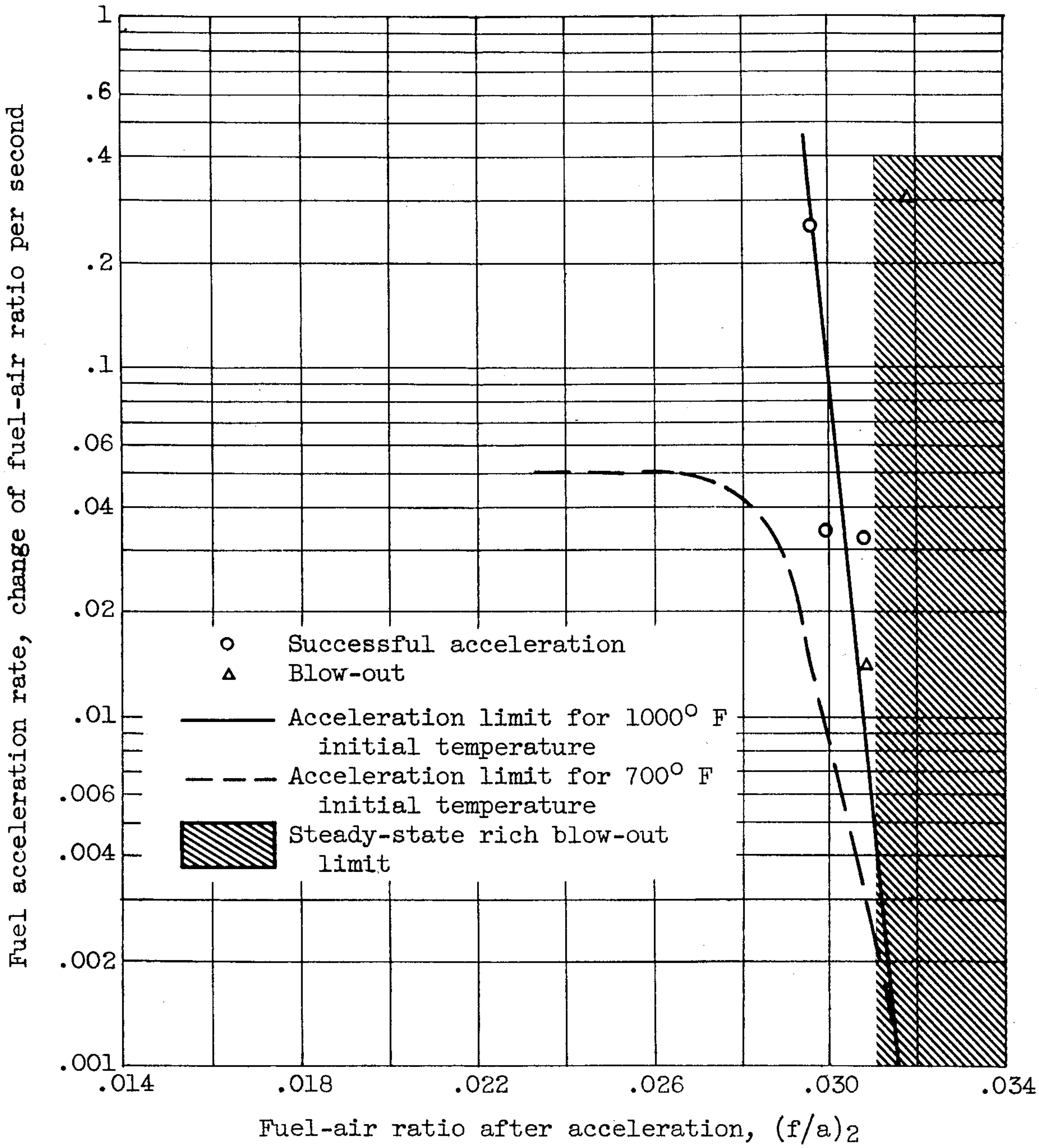


Figure 13. - Combustor fuel acceleration limits at two initial combustor-outlet temperatures. Air flow, 0.9 pounds per second; velocity, 82 feet per second; pressure, 9.3 inches of mercury absolute.

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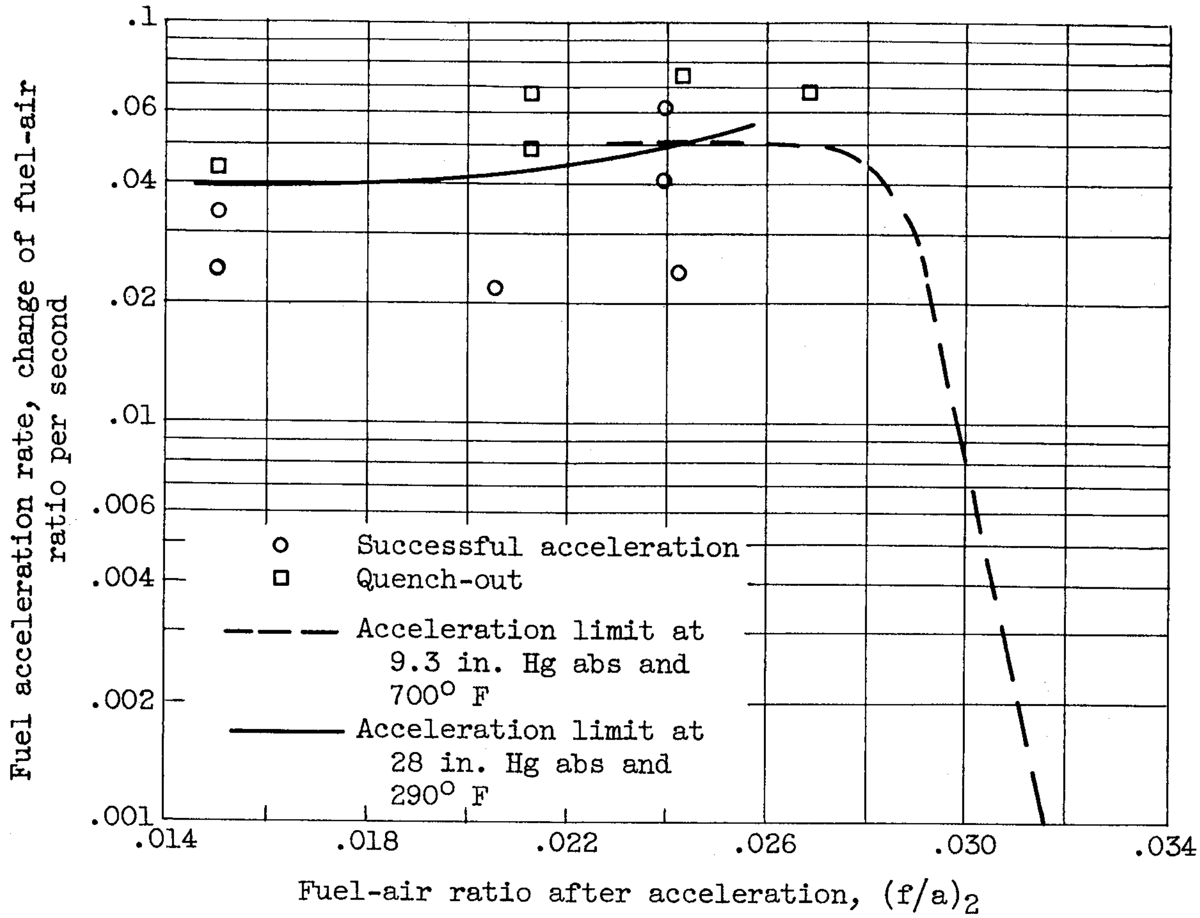

Figure 14. - Comparison of combustor fuel acceleration limits at inlet static pressures of 9.3 and 28 inches of mercury absolute for initial heat-release rate of 137 Btu per second; velocity, 82 feet per second.